2 TAI, K., FISCHER, R. J., SEABURY, C. W., OLSSON, N. A., HUO, T.-C. D., OTA, Y., and CHO, A. Y.: 'Room-temperature continuous-wave vertical-cavity surface-emitting GaAs injection lasers', *Appl. Phys. Lett.*, 1989, **55**, pp. 2473–2475

3 JEWELL, J. L., LEE, Y. H., SCHERER, A., MCCALL, S. L., OLSSON, N. A., HARBISON, J. P., and FLOREZ, L. T.: 'Surface-emitting microlasers for photonic switching and interchip connections', *Opt. Eng.*, 1990, **29**, pp. 210–214

4 KARIN, J. R., MELCER, L. G., NAGARAJAN, R., BOWERS, J. E., CORZINE, S. W., MORTON, P. A., GEELS, R. S., and COLDREN, L. A.: 'Generation of picosecond pulses with a gain-switched GaAs surface-emitting laser', *Appl. Phys. Lett.*, 1990, **57**, (10), pp. 963–965

5 TSUCHIYA, X., TAKESHIMA, A., INUZUKA, E., SUZUKI, K., KOISHI, M., and KINOSHITA, K.: 'Universal streak camera'. Proc. 16th Int. Congress on High Speed Photography and Photonics, SPIE, 1984, **491**, pp. 86–94

6 LAU, K. Y.: 'Gain switching of semiconductor injection lasers', *Appl. Phys. Lett.*, 1987, **52**, (4), pp. 257–259

520

Yb^{3+} SENSITISED Er^{3+} DOPED SILICA OPTICAL FIBRE WITH ULTRAHIGH TRANSFER EFFICIENCY AND GAIN

Indexing terms: Optical fibres, Amplifiers

Efficient 1·54 μm emission under 1064 nm excitation of Er^{3+}/Yb^{3+} codoped silica fibre is reported. The energy transfer efficiency from Yb^{3+} to Er^{3+}, ~95%, even under high inversion, is comparable to that in multicomponent glass fibres. The small signal gain of ~45 dB is measured and power amplifiers with 145 mW output power demonstrated.

Introduction: Codoped fibres are an attractive means of alleviating constraints on pump source, by energy transfer between ions. The Yb^{3+}/Er^{3+} system broadens the choice of pump source in Er^{3+} doped optical fibre amplifiers (EDFA) because Yb^{3+} exhibits a broad absorption band between 800 and 1100 nm. Efficient energy transfer between these ions is known and an amplifier has been demonstrated[1] using multicomponent glass (soft glass) fibres. However, these fibres suffer drawbacks, not least their incompatibility with standard fibres. Previous experiments with silica fibres were unsuccessful due to inefficient energy transfer. The limiting factor is the relatively long lifetime, 4 μs, of the $^4I_{11/2}$ band of Er^{3+}, which allows significant back transfer to Yb^{3+}, with corresponding loss of inversion. Lattice vibration energies of phosphates are higher than those of silica (1325 cm^{-1} compared with 1190 cm^{-1}) and so reduce the stability of the $^4I_{11/2}$ band, with a corresponding decrease in back transfer rate.

The soft glass fibres employed comprise multicomponent phosphates[2] doped with ~10% (12 wt.%) of Yb^{3+} and Er^{3+} to ensure small ion–ion separation. However, our results show that Al_2O_3 added to a P_2O_5–SiO_2 core fibre to enhance dopant ion solubility does not compromise either the phonon energy or compatibility with standard fibre.

Fibre fabrication: The silica based fibres were manufactured by solution doping.[3] An unsintered P_2O_5–SiO_2 frit is formed, via MCVD, to which the rare-earth ions and Al_2O_3 are added from solution. Soft glass fibres were prepared by the rod-in-tube method from Schott glasses, SEP4 (core) and APC7 (clad). All fibres were singlemoded at 1064 nm and parameters are listed in Table 1 with relevant bulk glass characteristics.

Table 1 PHYSICAL CHARACTERISTICS OF TEST SAMPLES

Sample	Fibre	Core composition	*NA*	$[Er^{3+}]$	$[Yb^{3+}]$
		mol.%		ppm	ppm
1	ND542	$P_2/Al_2/Si$: 2/4/94	0·15	900	0
2	ND539	$P_2/Al_2/Si$: 2/11/86	0·23	550	4500
3	ND715	$P_2/Al_2/Si$: 6/5/89	0·15	880	7500
4	SG237	$P_2/Al_2/Si$: 53/9/0	0·14	1000	90000
	Bulk SEP4	$P_2/Al_2/Si$: 53/9/0	/	1000	90000

The composition of SEP4 is well known, but key parameters have been converted to mol.% for ease of comparison with the silica fibres. Doping levels were determined from spectral loss and absorption cross-section data.[4,5] The high level of Yb^{3+} hinders measurement and large errors arise but materials analysis, in progress, will determine these values more accurately.

Doping levels and the ratio[6] of ~1 : 10 Er^{3+} : Yb^{3+} in SiO_2 were chosen from the literature.

Experiment results:

(*a*) *Emission decay times:* The effects of codoping and of host on the emission decay time τ of the $^4I_{13/2}$ Er^{3+} level were assessed and results are listed in Table 2. τ in the silica fibres is unaffected by the change in ratio of P_2O_5 to Al_2O_3, or by the presence of Yb^{3+}, being ~10·4 ms in each case. τ is reduced in the soft glass fibre due to diffusion of ions during fibre drawing and can be only partially overcome. Fibre 4 has the highest value, 7·3 ms, we have achieved in a singlemode SEP4/APC7 fibre which must be regarded as a limiting factor.

Table 2 SPECTRAL CHARACTERISTICS OF TEST SAMPLES

Sample	$\tau\{^4I_{13/2}\}$	λ_p	$\Delta\lambda$	Laser threshold (mW absorbed)	Laser slope
	ms	nm	nm		%
1	10·2	1532	52	/	/
2	10·4	1531	52	/	/
3	10·8	1535	34	37	27
4	7·3	1535	42	110	24
Bulk SEP4	9·5	1535	41	/	/

(*b*) *Fluorescence spectra:* Emission from the four fibres, under 810 nm excitation, are presented in Fig. 1 with peak wavelengths λ_p and integrated linewidths $\Delta\lambda$ listed in Table 2. Several features are noted. The spectra of fibres 1 and 2 are nearly identical, indicating that the output is independent of the presence of Yb^{3+}. The emission from fibre 3 is similar to

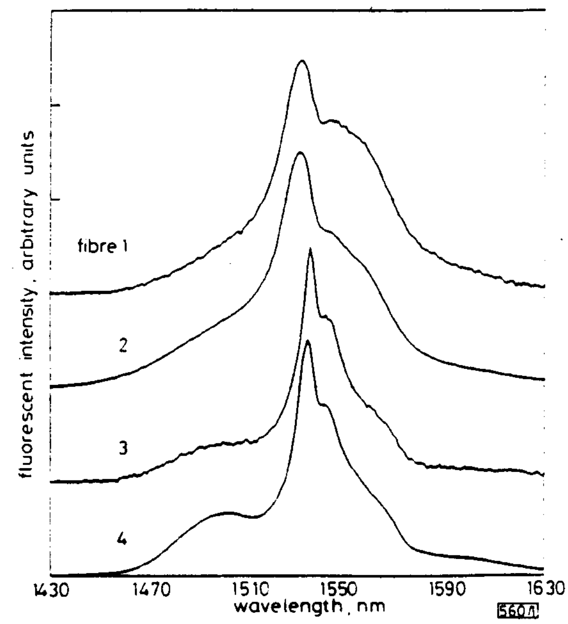

Fig. 1 *Fluorescence spectra of fibre samples under 810 nm excitation*

that of the soft glass (fibre 4) being spectrally narrower and λ_p shifted to longer wavelengths.

(c) *Laser characteristics:* The effect of host on energy transfer efficiency, η, was assessed from the laser threshold and slope efficiency, under 1064 nm excitation by a mini-Nd : YAG laser with cleaved fibre ends employed as mirrors (4% reflection). All data are presented for the optimum fibre length. No fluorescence can be generated in fibre 1 and η of 2 was too low to exhibit laser action, even at the maximum pump power, 250 mW, indicating a gain of less than 14 dB. Laser characteristics for 3 and 4 are listed in Table 2. The silica based fibre 3 shows a lower threshold T and higher slope efficiency than the soft glass. Normalisation of T for differences in NA and τ increases the value to 42 mW and then 60 mW. However, the difference is predominantly due to a higher (83%) gain coefficient of the silica fibre.

(d) *Amplifier performance:* A counterpropagating EDFA was built, with mini-Nd : YAG laser pump source. 40 dB of system gain was observed with an unoptimised system loss of 5 dB (fibre gain 45 dB). Power amplifier data (Fig. 2) show an output of 52 mW (17·2 dBm) for 135 mW absorbed, and a slope efficiency of 38%. A dual pump source, bidirectional configuration (365 mW of pump) gives an output saturation power of 145 mW (21·6 dBm) for 19 mW launched signal.

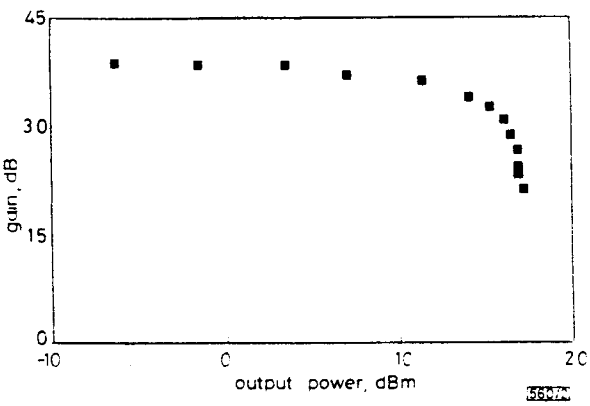

Fig. 2 *Saturation characteristics of prototype amplifier with counter-propagating 1064 nm pump source and employing ND715 as active fibre*

Summary: Yb^{3+}/Er^{3+} codoped silica fibre exhibiting the high energy transfer effficiency normally associated with soft glasses, yet compatible with standard fibre has been produced. Device characteristics confirm the fibre retains high transfer efficiency under high inversion. Gains of 45 dB, in excess of those achieved in a nominally optimised soft glass have been achieved. An optical power amplifier employing a convenient pump source with 21·6 dBm has been demonstrated.

Acknowledgments: This work was sponsored by the Amoco Technology Company and the SERC funded a research fellowship (JET). The Optoelectronics Research Centre is an SERC supported interdisciplinary Research Centre.

J. E. TOWNSEND
W. L. BARNES
K. P. JEDRZEJEWSKI*

Optoelectronics Research Centre
University of Southampton SO9 5NH, United Kingdom

S. G. GRUBB

Amoco Technology Company
Physical Technology Division
Naperville, Il70566, USA

* Permanent address: Institute of Electronics Fundamentals, Warsaw University of Technology, Poland

12th August 1991

References

1 GRUBB, S. G., CANNON, R. S., WINDHORN, T. W., VENDETTA, S. W., LEILABADY, P. A., ANTON, D. W., SWEENEY, K. L., BARNES, W. L., TAYLOR, E. R., and TOWNSEND, J. E.: 'High power sensitised erbium optical fibre amplifier'. OFC '91, San Diego, USA, PD7-1-4
2 Schott Glass Technology Inc., USA
3 TOWNSEND, J. E., POOLE, S. B., and PAYNE, D. N.: 'Solution doping technique for the fabrication of rare-earth doped optical fibres', *Electron. Lett.*, 1987, **23**, pp. 329–331
4 BARNES, W. L., LAMING, R. I., TARBOX, E. J., and MORKEL, P. R.: 'Absorption and emission cross sections of Er^{3+} doped silica fibres', *IEEE J. Quantum Electron.*, 1991, **QE-27**, pp. 1004–1010
5 SMITH, H., and COHEN, A. J.: 'Absorption spectra of cations in alkali-silicate glasses of high u.v. transmission', *Phys. & Chem. Glasses*, 1963, **4**, pp. 173–187
6 GAPONTSEV, V. P., MATITSIN, S. M., ISINEEV, A. A., and KRAVCHENKO, V. B.: 'Erbium glass lasers and their applications'. Conf. Lasers '81, USA, pp. 1135–1141

MEASUREMENT OF PUMP INDUCED REFRACTIVE INDEX CHANGE IN ERBIUM DOPED FIBRE AMPLIFIER

Indexing terms: Optical fibres, Amplifiers, Refractive index profiles

What the authors believe to be the first spectral measurements of pump induced refractive index change in the erbium doped fibre amplifier (EDFA) are reported. The measurements were performed using a 980 nm pumped EDFA configured within a quadrature locked interferometer. A maximum pumped/unpumped change in refractive index of $5{\cdot}5 \times 10^{-8}$ per dB of absorption at 1·536 μm was measured. The spectral dependence of the refractive index associated with the $^4I_{13/2}$–$^4I_{15/2}$ resonance transition was calculated by application of the Kramers–Kronig relations to the change in transmission data and was shown to be consistent with the experimentally measured data. The dispersion associated with the pumped index change was also calculated and systems implications are considered.

Introduction: Erbium doped fibre amplifiers are becoming important components in 1·55 μm optical fibre communications systems.[1] These amplifiers are being used in increasingly demanding applications (such as ultralong soliton systems and soliton laser sources) and it is therefore important to have a sound fundamental understanding of their characteristics. The amplification provided by such devices is produced by optical pumping of an absorption band to provide gain in the signal emission band. Around an absorption or emission band the refractive index is a strong function of wavelength. The Kramers–Kronig equations describe the relation between the spectral dependences of absorption and refractive index. This relationship indicates that there should be a refractive index change at the signal wavelength in an optical amplifier between the pumped and unpumped states.[2] Such a change could be of importance in soliton systems[3] and doped fibre devices, and may have applications in optical switching. This Letter describes a theoretical and experimental study of this effect in an erbium doped silica glass singlemode fibre amplifier pumped at 980 nm.

Measurements: A 1·5 m length of erbium doped $SiO_2 : Al_2O_3GeO_2$ singlemode fibre was used in this work. The dopant level was quite low giving a peak absorption of 3·7 dB/m at 1·535 μm. The 980 nm output from a Ti : sapphire laser was chopped at ~1 Hz and was launched into the fibre. A signal, from a tunable long external cavity (LEC) laser was counterdirectionally launched. The pumped–unpumped change in transmission was measured for many wavelengths between 1·4 and 1·6 μm. This data is plotted in Fig. 1. Also shown in the figure is the theoretically predicted change in refractive index. This was calculated by applying the Kramers–Kronig relations given in Reference 4 to the experimentally measured change in transmission data around the $^4I_{13/2}$–$^4I_{15/2}$ absorption band.

To measure pumped–unpumped change in refractive index the fibre amplifier was placed in one arm of a fibre Mach-